

Maneuver-Based Battery-in-the-Loop Testing - Bringing Reality to Lab

Oguz H. Dagci
AVL Powertrain Engineering Inc.

Nicolas Pereira
AVL France SAS

Jeff Cherry
US Environmental Protection Agency

ABSTRACT

The increasing numbers of hybrid electric and full electric vehicle models currently in the market or in the pipeline of automotive OEMs require creative testing mechanisms to drive down development costs and optimize the efficiency of these vehicles. In this paper, such a testing mechanism that has been successfully implemented at the US Environmental Protection Agency National Vehicle and Fuel Emissions Laboratory (EPA NVFEL) is described. In this testing scheme, the units-under-test consist of a battery pack and its associated battery management system (BMS). The remaining subsystems, components, and environment of the vehicle are virtual and modeled in high fidelity. The complete testing system includes the battery pack, battery management system, battery cyclers, battery test automation system, and hardware-in-the-loop (HIL) simulation platform that includes powertrain simulation software, vehicle dynamics simulation software, and various electronic systems for real-time model execution and communication. In the HIL simulation platform, first the roads and maneuvers which the vehicle will follow are defined with related traffic conditions. The intelligent driver in the vehicle dynamics simulation software sends control commands to the powertrain simulation software to achieve the reference maneuver on the given road. The desired battery power calculated in the powertrain simulation software is transmitted to the battery cycler for execution. As seen from the list of software packages and hardware/software components contained in this test system, ensuring that all of these components and subsystems (virtual or real) function seamlessly in real-time is a significant challenge. In addition to the system architecture and its benefits, these challenges and how they are solved are described in detail.

CITATION: Dagci, O., Pereira, N. and Cherry, J., "Maneuver-Based Battery-in-the-Loop Testing - Bringing Reality to Lab," *SAE Int. J. Alt. Power.* 2(1):2013, doi:10.4271/2013-01-0157.

INTRODUCTION

Stringent emission and fuel economy regulations and strong competition force the automotive and heavy duty truck OEMs to invest in advanced vehicle and powertrain technologies and architectures. Increasing vehicle system complexity to comply with the regulations in order to compete in the market does not guarantee the success. Automotive OEMs and suppliers must design systems, subsystems, and components that meet both regulatory/market requirements and profitability targets. As seen in [Figure 1](#), the regulatory requirements can be met by using three different systems. The red dot in the figure represents a suboptimal system that meets the regulations but penalizes

profitability. If this system could be optimized with further expenditure of resources, system cost would decrease indirectly as shown as orange dot in the figure due to higher retail pricing potential as a result of the improved fuel economy. This option can be risky as a higher price might not be accepted by the target customer group due to its income level or product image. The best option would be the green dot where a simpler less costly but optimal system achieves the same performance and fuel economy.

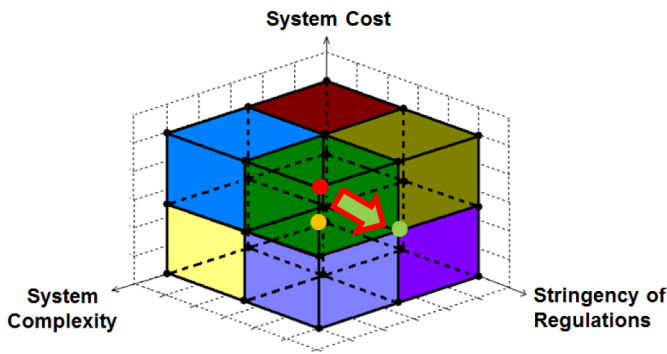


Figure 1. Options to Meet Stringent Regulations

The resulting question for vehicle design is what kind of design methodologies would enable system optimization with limited resources, time, and budget. One of the methods employed to evaluate combinations of new technologies is the hardware-in-the-loop (HIL) simulation technique where subsystems and components are tested and optimized in a system context. This allows for a more cost effective and shorter product development process due to the reductions in the number of prototype iterations and more flexible testing options. HIL has been widely used in the automotive industry over the last decade. Some of its application areas are ECU-in-the-loop [1,2,3], engine-in-the-loop [4,5,6,7], ABS-in-the-loop [8, 9], BCU-in-the-loop [10, 11], Aftertreatment Controller-in-loop [12], Transmission-in-the-loop [13,14,15], Hybrid Energy Management Controller-in-the-loop [16]. In all of these applications, the unit-in-the-loop is the actual hardware and the rest of the vehicle system and/or its subsystems are virtual models running in real time on a computing platform.

Although hybrid electric and full electric vehicles exist in the product portfolio of almost every automotive OEM, there is not much activity in the design of battery-in-the-loop test systems from a holistic approach. In contrast, HILs [17,18,19] focus only on the battery as a component and lack the vital system perspective needed to attain the green dot in Figure 1. In this paper, a unique battery-in-the-loop system designed to use realistic scenarios and to integrate the battery with full vehicle simulation models being developed by the agency is going to be described [21]. In addition to EPA, we expect that OEMs, suppliers, researchers and other regulatory organizations will find the system to be a valuable tool to validate and optimize batteries, hybrid architectures and related control, diagnostic and safety algorithms, especially during the early stages of vehicle development.

VALUE OF A SPECIAL BATTERY-IN-THE-LOOP SYSTEM

Today, it is apparent that the number of hybrid electric and full electric vehicle models has been increasing consistently in the portfolio of automotive OEMs in order to meet consumer demand for more efficient vehicles in the face

of rising fuel costs and to prepare for the new regulatory requirements. Moreover, EPA and NHTSA have incorporated a Mid Term Evaluation of the 2017-2025 greenhouse gas and CAFE standards when new technologies will be evaluated. In the context of this period of major technological transition in the automotive industry, EPA analytical and regulatory work, OEMs and suppliers will benefit in several ways from this improved method for evaluating electric-drive vehicles and systems. These include:

1. Supporting complete technical evaluation of electrified vehicles and their components.
2. Allowing more accurate testing of systems when full vehicle chassis testing is too costly or not feasible.
3. Allowing more comprehensive testing than engine (or even battery) tests alone.

The battery is just a part of a complex system that cannot be fully optimized by focusing on only this one component. Therefore, a holistic approach is needed where the complete vehicle including the battery is optimized. This approach includes the application of various simulation techniques using high fidelity physics based models that represent the hardware's operation in wide range operating conditions. In many cases, these techniques are mature and have been used successfully for conventional technologies in the automotive industry for many years. The battery system is one of the subsystems which cannot be accurately modeled for automotive performance and durability simulations. As a result, a battery-in-the-loop system would meet all the expectations from a simulation system which moves the system integration, optimization, and validation to earlier stages of the vehicle development process. The battery-in-the-loop system that will be described in detail in the following sections contains an actual battery and battery management system (BMS) and the remaining subsystems, components, and environment of the vehicle are modeled in high fidelity, runs in real-time, and its system parameters can be modified seamlessly even while the test is being conducted.

Moreover, as GPS, navigation systems, telematics systems and services have become an integral part of modern vehicles, powertrain control units now have access to spatial and aspatial information including 3D-road topography, road features (stop signs, traffic lights etc.), the vehicle's most probable path along with historic and real-time traffic data. This opens up many new possibilities to optimize fuel economy and battery usage. Some of these potential uses are:

- Smart cruise control that matches the vehicle speed to the road ahead to avoid harsh braking and acceleration
- Optimized air conditioning control to enable engine off at vehicle stops

- The battery-in-the-loop system described in this paper enables all these optimizations to be performed faster, cost and time efficient, and most importantly realistically thanks to the high fidelity dynamic vehicle models, 3D environment models, powertrain models and the utilization of an actual vehicle battery system.

Figure 2 shows the overall structure of the battery-in-the-loop system implemented at EPA. As described below, this system can be used in three different ways, independently or in combination.



A complete vehicle model including all vehicle components (including a battery model) executes within the PC based simulation platform. Major model/program development, debugging tasks and test simulations are performed efficiently in this offline environment.

The complete system parameterization can be reused from the previous method (offline simulation) except the battery model. The simulation platform is now connected to an external battery model, part of the battery test automation system. The same test run can now be run in real-time with an emulated battery of the battery test automation system, integrating safety strategies and different testbed procedures before connecting the actual battery. In this application, all the components shown in [Figure 2](#) except the battery cycler and the unit-under-test are used.

The third application of the system is to replace the battery model in the battery test automation system with the actual battery. The actual battery pack is now stimulated by the battery cycler and its actual electrical characteristics feed the powertrain model in the HIL system.

```
graph TD; A[The Driver compares the vehicle state with the target he has to reach (e.g. speed limit).] --> B[The Driver requests some acceleration, pushing the gas pedal.]; B --> C[The pedal position is interpreted by the powertrain model and a corresponding Power is requested to the battery.]; C --> D[The automation system makes sure the requested Power remains within the security boundaries and triggers the cyclor unit.]; D --> E[The real battery delivers Voltage and Current.]; E --> F[The powertrain model is fed.]; F --> A;
```

The Driver compares the vehicle state with the target he has to reach (e.g. speed limit).

The Driver requests some acceleration, pushing the gas pedal.

The pedal position is interpreted by the powertrain model and a corresponding Power is requested to the battery.

The automation system makes sure the requested Power remains within the security boundaries and triggers the cyclor unit.

The real battery delivers Voltage and Current.

The powertrain model is fed.

500 Hz

The system in Figure 2 consists of four major subsystems: Unit-Under-Test, Battery Cycler, Battery Test Automation and Simulation Platform.

The Unit-Under-Test

The unit-under-test used in the initial tests consists of a Li-Ion battery pack and the associated BMS. Some of the battery pack specifications are listed in [Table 1](#).

Table 1. Battery Pack Technical Specifications

Discharge Power	67 kW continuous 204 kW (10 sec.)
Charge Power	-24 kW continuous -125 kW (10 sec.)
Vmax	428 V
Vnom	393 V
Vmin	298 V
Capacity	22.8 kWh
Weight	288 kg

Battery Cycler

In this system architecture, the battery cycler stimulates the battery with commands from the battery test automation system. It dynamically discharges/charges the battery pack at the desired power level determined by the powertrain and vehicle simulators on the HIL simulation platform.

The battery cycler used in this configuration is the ± 250 kW AeroVironment AV-900.

Battery Test Automation System

The battery test automation system can be considered a gateway between the battery related hardware components (battery pack, BMS, cycler) and the vehicle simulation platform in the current setup. The system communicates with the battery cycler, BMS, battery heating/cooling system and test cell while collecting parameters such as battery voltage, current, SOC and temperature for use by the HIL simulation platform and simultaneously for display on a customizable GUI. A wide variety of safety logic can be implemented to prevent any misuse of the battery or related equipment. AVL Lynx is used as the battery test automation system in this configuration. [Figure 4](#) shows a representative display of the Lynx user GUI as it is used to control test operations.



Figure 4. Lynx GUI to Control Test Operations

HIL Simulation Platform

The HIL simulation platform consists of the vehicle dynamics simulator, powertrain simulator, and other tools for software calibration, control algorithm development and data monitoring and collection. The HIL simulation platform executes these components in real-time.

AVL InMotion shown in [Figure 5](#) is used as the real-time simulation framework. It is an open simulation platform integrating vehicle dynamics simulator, powertrain simulator and other development tools. IPG CarMaker is the main software component of this framework. It simulates driver behavior, the environment including roads and traffic conditions and vehicle dynamics including chassis, suspensions, tires and aerodynamic characteristics of the vehicle.

The driver model with artificial intelligence is one of the key features of the complete system. The straightforward parameterization allows the system to simulate and study different driving styles (e.g. defensive, normal or aggressive), city courses or handling tracks, driving uphill, downhill, forward or backward, compliance cycles, stop & go and parking maneuvers.

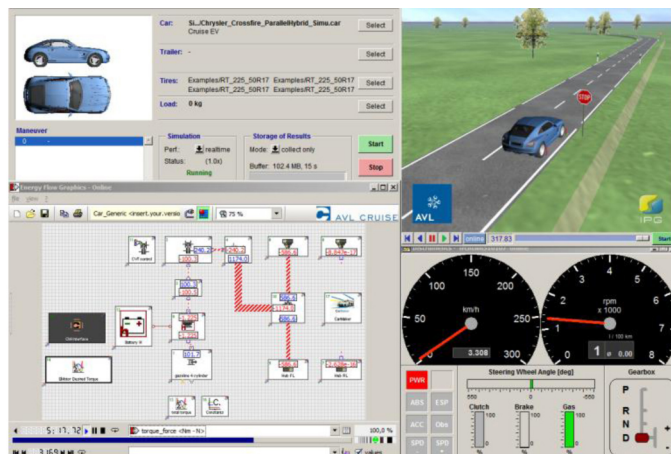


Figure 5. AVL InMotion Software Platform

The simulation of the complete vehicle environment as shown in [Figure 6](#) brings on-road reality to the testbed. Within the same test run the vehicle can drive in virtual situations such as traffic jams, intersections, flat/uneven roads, low friction areas, freeway, or actual digitized tracks.



Figure 6. Test Run Example including Traffic & Pedestrians